Understanding Near-surface and In-Cloud Turbulent Fluxes in the Coastal Stratocumulus-Topped Boundary Layers

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LONG-TERM GOAL

The long-term goal of this project is to understand the spatial and temporal variation of the surface fluxes in relation to the variability of the sea state and the stratocumulus-topped boundary layers and to improve the physical parameterizations of surface flux and boundary layer processes in regional and climate models.

OBJECTIVES

The objective of this project is to understand the spatial and temporal variability of the turbulent fluxes in relation to the sea state and the stratocumulus-topped marine atmospheric boundary layers (MABL) properties. Our work in FY05 focused on the detailed analysis of errors and possible corrections in near surface turbulence fluxes from aircraft measurements due to sampling issues and the vertical structure of the marine boundary layer at cross sections to north and in the center of Monterey Bay. The analysis of aircraft data was supplemented by data from other measurement platforms during the Autonomous Oceanographic Sampling Network (AOSN-II) Experiment co-sponsored by the Monterey Bay Aquarium Research Institute (MBARI) and ONR.

APPROACH

Our analyses in the previous year (FY04) showed significant deviations between bulk parameterization schemes of the surface turbulence fluxes and the fluxes estimated from near sea surface aircraft data using the eddy covariance method. However, questions remain on using the aircraft measured turbulence to represent 'surface' flux. Thus, we use spectral analyses to evaluate data quality and sampling limitations of the airborne sensors. In addition, we also obtained wave state, surface currents, and synoptic conditions in the experimental area from publicly available data sources. Vertical profiles of the boundary layer from aircraft soundings are also incorporated into the analysis of the aircraft turbulence data.

Qing Wang is responsible for the overall project. Dr. John Kalogiros, an external research associate from National Observatory of Athens, Greece, works on the error analysis and the possible corrections using a variety of data sources. In situ observations were made by the Twin Otter research aircraft operated by the Center for Interdisciplinary Remote Piloted Aircraft Studies (CIRPAS) at the Naval Postgraduate School (NPS) during the AOSN-II experiment.

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14. ABSTRACT
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WORK COMPLETED

1. We gathered and compiled data from other measurement platforms to aid the analyses of the aircraft turbulent flux during the AOSN-II period. These include the surface met data from the nearby buoys, surface current from CODAR, satellite measurements (AVHRR and GOES satellites), and reanalysis field from NCEP/NCAR reanalysis. These data are valuable in providing a thorough understanding of the meteorological and oceanic background on a day-to-day basis.

2. We applied a detailed spectral analysis to the near sea surface aircraft data from AOSN-II to evaluate data quality and limitations induced by the sampling procedure.

3. We analyzed aircraft vertical soundings during AOSN-II flights in order to examine the vertical structure of the boundary layer. In particular, the spatial variation of the boundary layer depth in the measurement region is investigated.

4. Based on the boundary layer height and time variation of the mean quantities, we estimated the error using the calculated turbulence fluxes from the aircraft level as surface turbulent fluxes due to vertical flux divergence.

RESULTS

Spectral analysis of the near sea surface aircraft data. In addition to eddy covariance method, turbulent fluxes can be obtained through turbulent spectra in the inertial subrange and spectral similarity theory as an alternative approach. For this purpose, we made spectral analyses for all measurements in 2003 from near sea surface (30-40 m ASL) 10 km legs and examined the applicability of the surface spectral similarity. The results show that the along-wind cospectra follow the surface layer similarity at high frequencies and, thus, we can used inertial subrange similarity methods to estimate surface flux and the turbulent transfer coefficients. Figure 1 shows momentum turbulent transfer coefficient reduced to neutral conditions in comparison to the COARE 3.0 bulk algorithm. Only data with air-sea potential temperature difference greater than 0.5 K and u_* greater than 0.05 ms^{-1} are included.

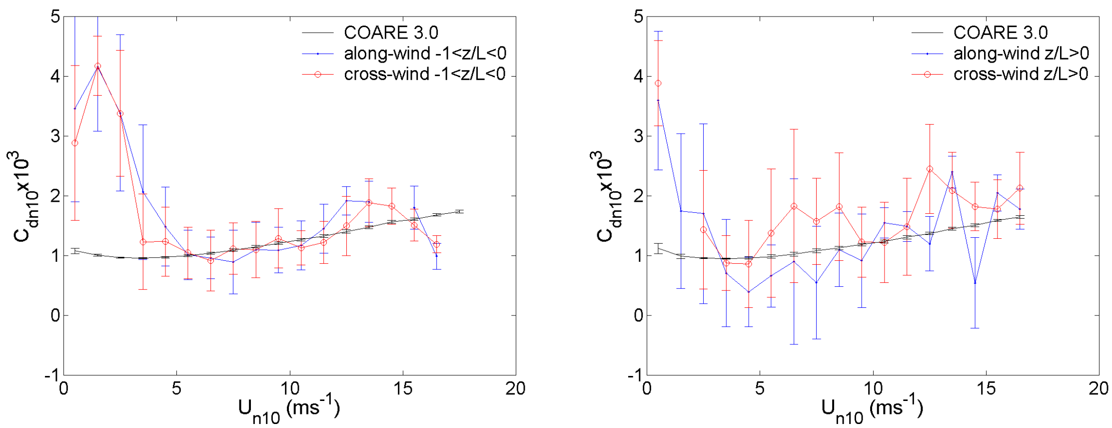

Figure 1: Neutral drag coefficient against neutral wind speed U_{n10} at reference height (10m) estimated from median values in wind speed bins of 1 ms^{-1} using the inertial dissipation similarity method. Error bars indicate the standard deviation.

Even though the results of the inertial subrange method generally agree better with the bulk parameterization scheme for the case of drag coefficient, the different behavior at low wind speed in both inertial subrange similarity and covariance methods (discussed in FY04 report) compared to the bulk estimates is the same. In addition, in both methods the same deviations from the bulk method are observed for the sensible heat transfer coefficient as well as for transfer coefficient of the mixing ratio of water vapor (not shown here). Thus, these discrepancies between measured and bulk transfer coefficients are probably not due to measurement errors but to entrainment or vertical flux divergence as a result of low boundary layer height, or swell at low wind speed in the present dataset. The flux loss effect due to low frequency sampling was estimated using the isotropic behavior of the inertial subrange and were found to be small (below 10%) except at very stable atmospheric conditions ($z/L>1$) which usually combined with low wind speed. The statistical random error of covariance fluxes due to finite averaging was estimated from theoretical formulae to be up to 30%. This error contributes to the scattering of estimated transfer coefficients but does not bias the results.

Variations of boundary layer height from aircraft soundings. Slant-path soundings were used to study the boundary layer vertical structure and the estimated boundary layer height Z_i base on the height of strong temperature inversion. Most soundings were on the "lines" defined by the green or red points (Fig. 2a). At offshore locations the boundary layer height was generally low (300 m on average) and inside Monterey Bay it was significantly lower (below 100 m). Surface buoyancy flux was found to be a dominant factor in the determining the observed boundary layer heights (Fig. 2b), except for buoyancy flux below 0.1 Wm^{-2}. While uncertainties in large scale subsidence and entrainment can be used to explain the scattering in relative high buoyancy flux conditions, the dominant forcing from vertical wind shear may explain the uncorrelation between boundary layer height and buoyancy flux under weak buoyancy forcing.

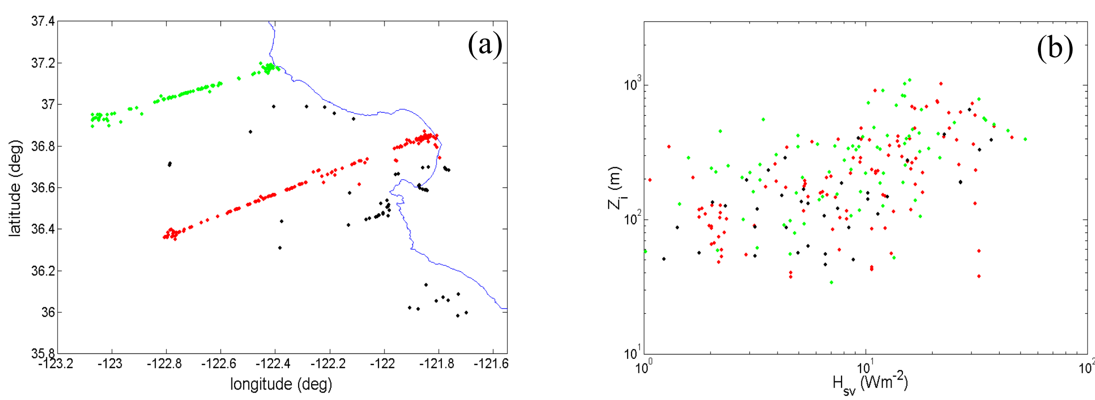

Figure 2: Locations where boundary layer heights (Z_i) are identified from aircraft soundings (a) and Z_i as a function of near-surface buoyancy flux H_{sv} from AOSN-II 2003 dataset.

Using the sawtooth soundings it was possible to make cross sections of the lower atmosphere layer structure at the "lines" of the soundings. From these crosssection plots, the collapse of the boundary layer inside the Monterey Bay can be clearly seen (not shown here). The collapse of the boundary layer which was typical for most of the flights is likely due in most cases to the lee-wave sheltering effect of coastal mountains at the north or south of the Bay and the corresponding low wind and

turbulence in the Bay. These are the cases where aircraft measurements need to be corrected is they are used to represent the 'surface' fluxes (see results below).

Flux divergence correction for surface flux: Because boundary layer height was rather low, vertical divergence of turbulences fluxes between measurement altitude and reference height (10 m) in the surface layer was likely significant. A method based on the equations of state (budget) of mean quantities was used to estimate the flux divergence. The storage term of mean quantities was estimated using collocated flight legs separated in time by one hour or more. Horizontal gradients were estimated from the grid (5 km by 5 km) interpolated mean fields. Average values of estimated sum of advection, pressure gradient, and Coriolis terms in mean u and v equations were about 10^{-4}–10^{-3} ms^{-2}. The advection term in mean potential temperature (water vapor mixing ratio) equation was about 10^{-5}–10^{-4} Ks^{-1} ($gkg^{-1}s^{-1}$). Storage terms were on average about 10-20% of the total of the rest terms in the equations of mean u and v and about 40% in the equations of potential temperature and water vapor mixing ratio.

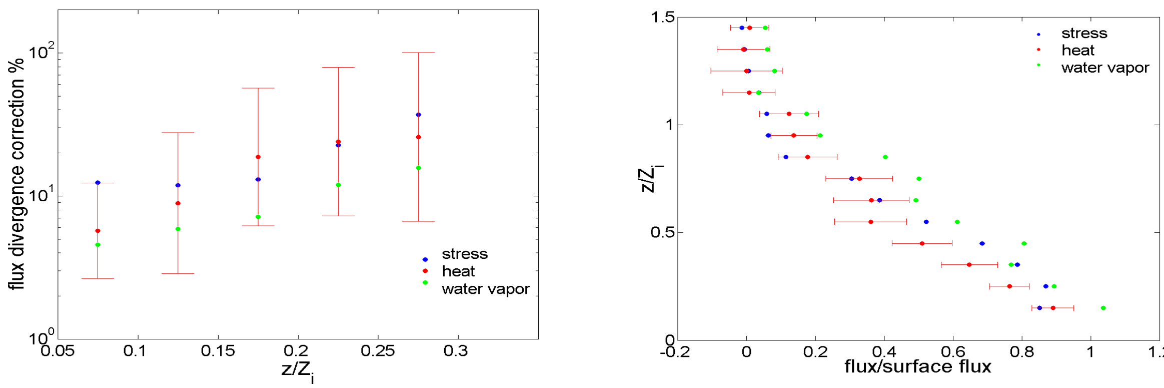

Figure 3: (a) Bin averaged momentum, heat and water vapor mixing ratio flux divergence correction vs. z/Z_i, where z is the measurement altitude (30 -40 m). (b) Composite (average normalized) profiles of fluxes from sounding data.

Figure 3 shows the bin averaged flux divergence corrections for the entire dataset. The averaging horizontal length for fluxes estimation was 10 km in Fig. 3a but only 1.5 km in Fig. 3b due to the need for high vertical resolution during the soundings. Only positive flux divergence estimations are included (turbulence reduction with height) and z/Z_i values between 0.05 and 0.3 where most cases belong. A 0.05 bin width of z/Z_i values was used. Also, only soundings with positive near surface flux, Z_i>150 m and lower measurement height less than $0.3Z_i$ are included in the averaging of the profiles. Error bars represent the standard deviation of observed values in Fig. 3a and the standard error of the mean profile in Fig. 3b for the case of heat flux. Averaged stress in Fig. 3 uses the stress component along the mean direction of the near surface wind. On average there was a small clockwise turning of wind direction and an increase of wind speed with height with a wind jet at the boundary layer top (not shown here). This is attributed to the effect of baroclinity in the coastal environment with a negative average local horizontal gradient of air temperature in the boundary layer in the cross-coast direction (cold air temperature close to the coast due to upwelling) and northerly wind on average.

Figure 3a shows that the flux correction is proportional to the z/Z_i , which is expected for linear profiles of the fluxes in the boundary layer. Values of z/Z_i above 0.3 correspond to Z_i less than 100 m

with low Z_i/L values (L is the Monin-Obukhov length). These are the cases when surface layer and the structure of the boundary layer are not clear and we do not expect the linear vertical profiles of fluxes. Water vapor flux showed small vertical divergence while momentum shows constant divergence (about 12% flux correction) at z/Z_i below 0.2. Fig. 3b shows that the flux profiles were linear on average based on the soundings. The heat flux profile seems to reach zero value at the top of the boundary layer similarly to momentum and water vapor fluxes. This result agrees with the similar divergence correction for all fluxes observed in Fig. 3a. Stress is also about constant up to $0.2Z_i$ which corresponds to the constant flux divergence correction for stress in Fig. 3a. Due to random statistical error individual profiles show significant deviations from a linear profile.

IMPACT/APPLICATIONS

Our observational analysis suggests that the bulk surface flux parameterizations used in mesoscale model deviate significantly from measured surface fluxes after careful calibrations/corrections. Further evaluation of the parameterizations is needed to correctly represent the coastal boundary layers and their effects on regional simulations.

TRANSITIONS

The results of this project will potentially help to improve the turbulence parameterizations of mesoscale models.

RELATED PROJECTS

Related project is the AOSN-II Experiment co-sponsored by MBARI and ONR.

SUMMARY

Spectral analysis of the near sea surface aircraft AOSN-II data showed different behavior between along and cross wind sampling directions. In cross wind sampling spectra showed a shift of 'energy' from lower to higher frequencies. Comparison of turbulent fluxes estimates from an inertial subrange similarity method and eddy covariance showed that the latter method underestimated the drag coefficient especially for along wind sampling. Other deviations between measured and bulk transfer coefficients that were noted for the results of the eddy covariance method in last year report were also seen in the results from the inertial subrange similarity method. Entrainment and flux divergence effects due to low boundary layer height and swell effects at low wind speed are probably the reasons for these deviations. Analysis of aircraft vertical soundings showed at offshore positions the boundary layer height was generally low (300 m on average) and inside Monterey Bay the boundary layer collapses to significantly lower values (below 100 m). Small buoyancy flux especially in the Bay is probably the reason for this behavior of the boundary layer. As a result of the low boundary layer height the flux divergence of the measured turbulence fluxes at 30-40 m above sea surface from actual surface fluxes was found to be significant.

PUBLICATIONS

Kalogiros, J.A., Q. Wang, S. Ramp, G. Buzorious, and H. Jonsson, (2005): Turbulence surface fluxes in the cloudy marine atmospheric boundary layer near the coast. *6th Conference on Coastal Atmospheric and Oceanic Prediction and Processes, American Meteorological Society*, San Diego, 9-13 January 2005.

Kalogiros, J.A., Q. Wang, S. Ramp, G. Buzorious, and H. Jonsson, (2006): Measurements and variations of surface turbulent fluxes in a costal environment; In preparation for submission to *Bound. Layrer Meteorol*.